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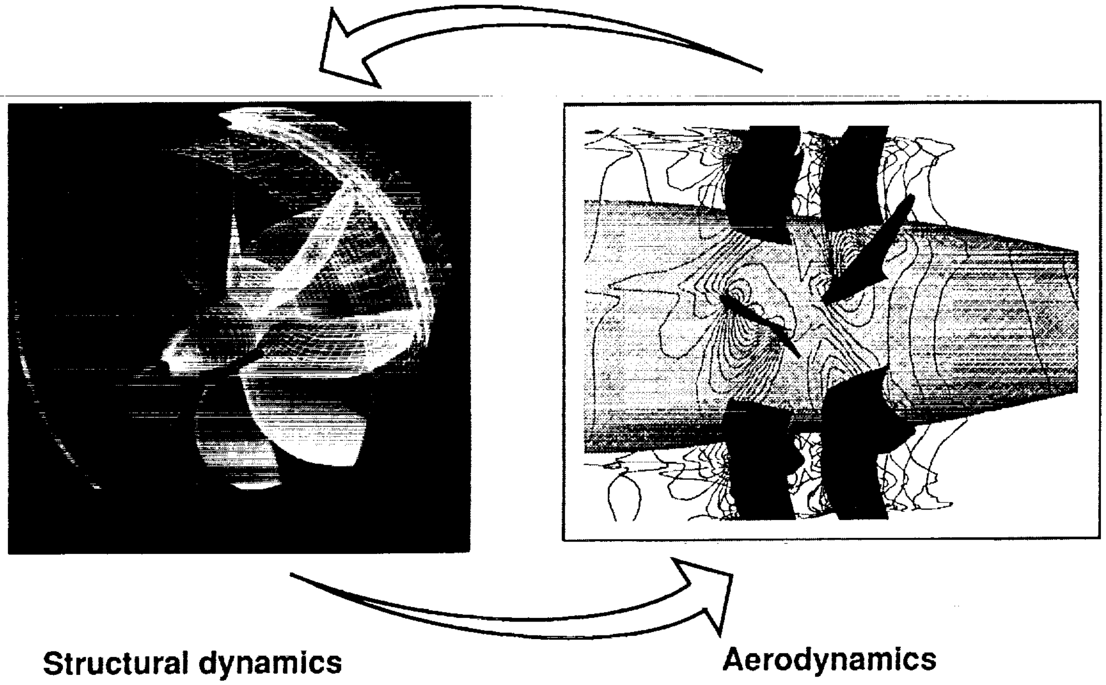
PROPULSION AEROELASTICITY, VIBRATION CONTROL, AND DYNAMIC SYSTEM MODELING

Bruce M. Steinetz
NASA Lewis Research Center
Cleveland, Ohio

Aeropropulsion research in the Structural Dynamics Branch is aimed at addressing two key objectives: conceiving and implementing innovative structural concepts to enhance the performance of advanced aeropropulsion systems and developing and validating analytical techniques to define the limits of dynamic performance of advanced aeroengines, prior to costly full-scale testing. Aeroelasticity, vibration control, and dynamic systems, are the three research areas that make up the Structural Dynamics Branch. In the aeroelasticity technical area, researchers use both analytical and experimental means to extend and define the structural performance limits of advanced propulsion systems, including future ultra-high-bypass ducted turbofans, advanced turboprops, and high power-density turbopumps. Vibration control researchers are developing and evaluating active control systems and the required high-speed robust electronic controls to minimize unwanted shaft vibration of both turbine-engines and rocket engine turbopumps. Researchers in the dynamic systems technical area are developing a new class of high-temperature dynamic engine seals required for advanced hypersonic (e.g., NASP) engines, as well as developing advanced space mechanism technology to enable future space missions. Central to each of the branch's technical areas is the development of advanced computational methods which using modern computer science, will fundamentally improve solution speed and accuracy of large scale structural dynamics problems.

Aeroelastic Methods



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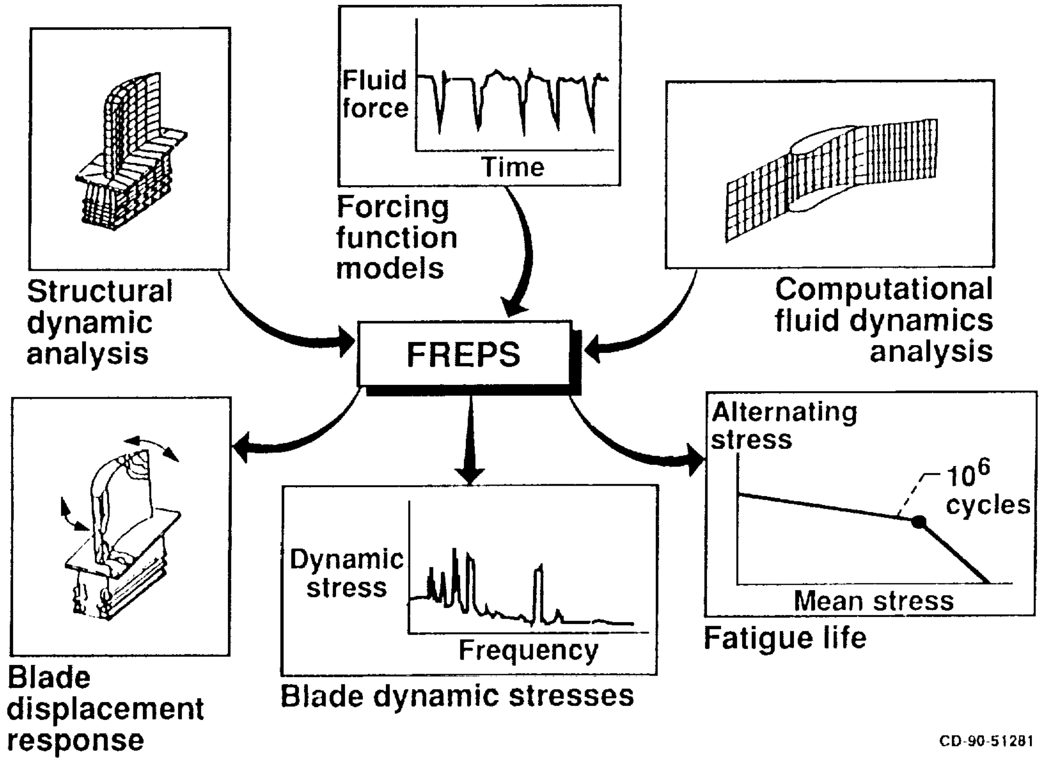
Aeroelastic methods are being developed and validated which can be used to define and in some cases extend the performance limits of aeropropulsion systems such as advanced ultra-high-bypass ratio ducted-fan engines and advanced turboprop engines. To predict the onset of the potentially dangerous condition of blade flutter (e.g., large amplitude blade vibrations caused by the interaction of unsteady air loads and blade natural frequencies), advanced computer codes which model the crucial blade/airstream interactions are being developed. Depending on the application, a wide spectrum of computer codes is used to define engine performance limits. The structural and aerodynamic models used in these codes increase in sophistication as the codes are developed. Examples of structural models used in increasing order of complexity are the spring-mass, continuous beam, and finite element representations. The geometry and materials used in modern blades require the finite element structural models for accurate analyses and are generally used for the final design.

The aerodynamic theories used model flow in the subsonic, transonic, and supersonic flow regimes. Examples of steady and unsteady cascade aerodynamic codes being developed in increasing order of complexity include the panel, full-potential, Euler, and Navier Stokes methods. The aeroelastic analyses are being developed to account for the effects of mistuning (e.g., small variations of blade-to-blade natural frequencies, blade angle of attack, etc.) that can lead to dangerous operating conditions in next-generation, high-performance blades.

Turbomachinery
Blade Forced REsponse Prediction System

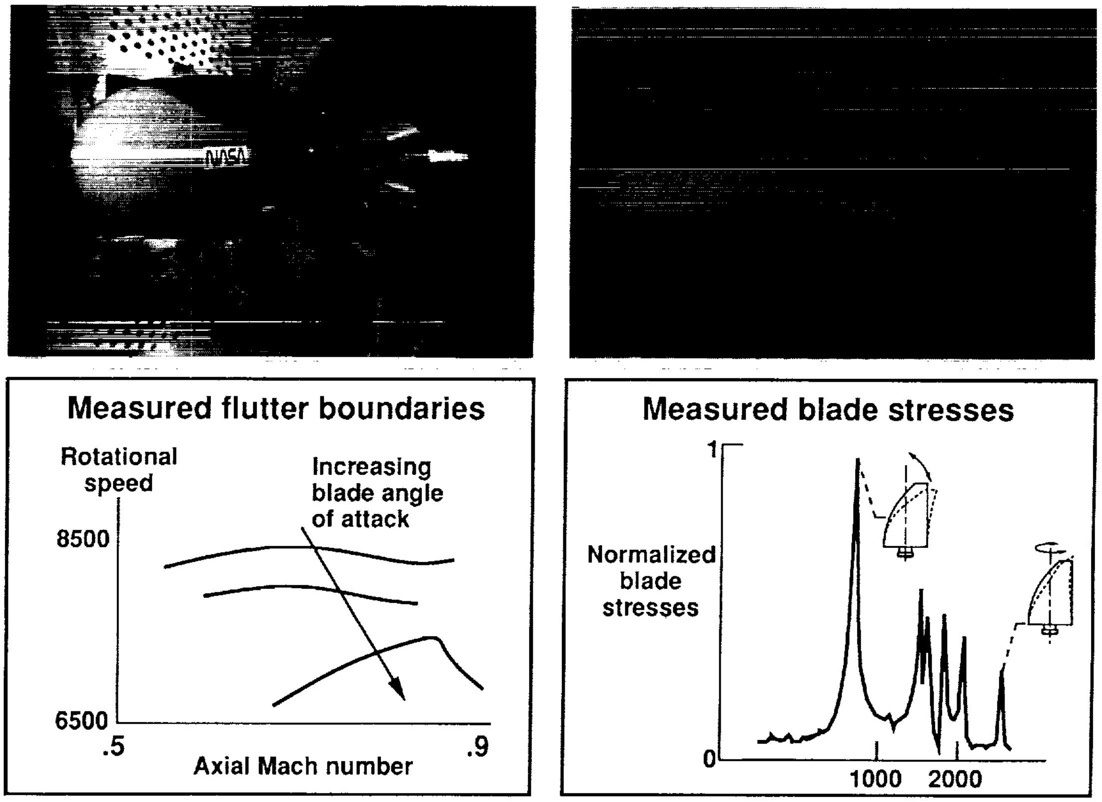


Once the dynamic blade performance limits have been defined, structural designers must then determine the dynamically induced blade stresses to enable improved prediction of blade fatigue lives.

A methodology to conduct this forced response analysis of highly loaded and cambered turbomachinery blades called FREPS (e.g., Forced Response Prediction System) is being developed by the Structural Dynamics Branch. This modal-based finite element method combines two-dimensional steady potential-flow and linearized unsteady potential flow with solid finite element structural analysis. After the blade natural frequencies and mode shapes have been computed, FREPS then calculates blade displacement response and cyclic blade stresses. Knowing the cyclic and steady blade stresses, designers can estimate through the use of the Goodman diagram the anticipated blade life. To validate the key elements of this methodology, experiments are planned to measure unsteady aerodynamic forcing functions and blade response.

FREPS is currently being applied to analyze the highly loaded, life-limited space shuttle main engine high-pressure-oxygen-turbopump blades that carry on the average 300-hp per blade.

Experimental Aeroelastic Research



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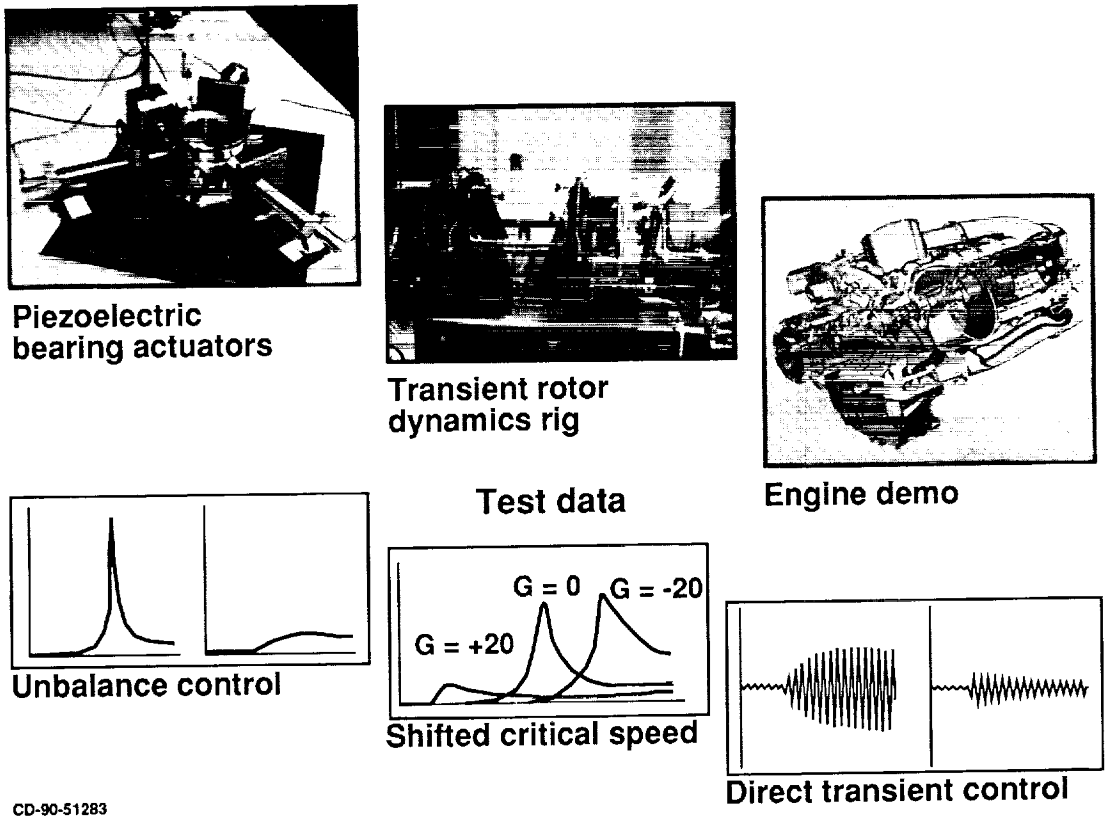
In conjunction with the engine industry and the Propulsion Systems and the Aeropropulsion Facilities and Experiments Divisions here at Lewis, experimental aeroelastic research is conducted to gain first-hand understanding of blade aeroelastic phenomena. The physical insight gained by the wind tunnel tests guides the analytical development, and the data collected are used to validate the complex analysis procedures. Blade performance parameters such as flutter boundaries and blade stresses are measured while operating scale propulsor models under simulated flight conditions in Lewis' wind tunnels and in a specialized vacuum spin rig. For instance, using advanced instrumentation techniques, such as laser-based blade vibration measurement system, flutter boundaries were measured for a counter-rotating propfan, as shown on the left.

Experimental research in the Structural Dynamics Branch is also addressing aeroelastic issues associated with energy efficient counterrotation propfans being considered for next generation cruise missiles. As shown in the figure on the right, blade vibrational mode shapes, natural frequencies and stress levels are determined through advanced experimental methods such as laser holography.

Active Control Of Rotor-Shaft Dynamics



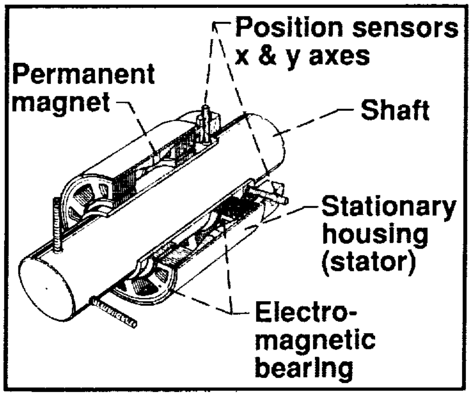
Two types of active control techniques are being pursued in the Structural Dynamics Branch to minimize unwanted shaft vibrations caused by unbalance, transient effects, or supercritical shaft-speed operation. In the first technique, piezoelectric actuators exert modulated control forces on the turbine shaft through soft-mounted shaft bearings.

In laboratory tests the piezoelectric actuators have been shown to be very effective in controlling the vibration of high speed shafts. For instance the peak vibration of a turbine shaft when passing through the first bending critical was reduced by a factor of 4. In another test, tuning the actuator/controller system to effect a different bearing stiffness allowed the shaft's critical speed to be shifted either above or below the normal critical speed by up to 50 percent. This feature of active control permits engine design strategies where operation of the shaft at critical speeds is not necessary. Using the transient rotor-dynamics rig shown in the figure, vibration response to transient events such as might occur during a blade loss or hard landing were reduced five-fold.

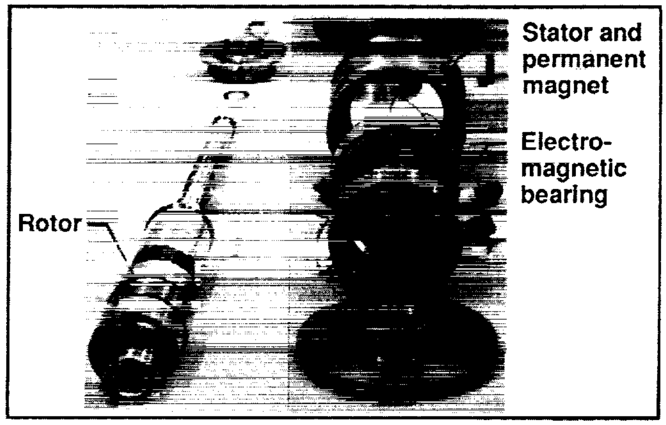
The above benefits of active vibration control can translate into substantial performance gains and weight savings in future turbomachines, removing vibrational constraints that presently limit engine design. Through a cooperative program with the Army, Allison, and Texas A&M, a T-63 helicopter demonstration engine is to be retrofitted with the piezoelectric shaft control system to quantify the installed dynamic performance benefits.

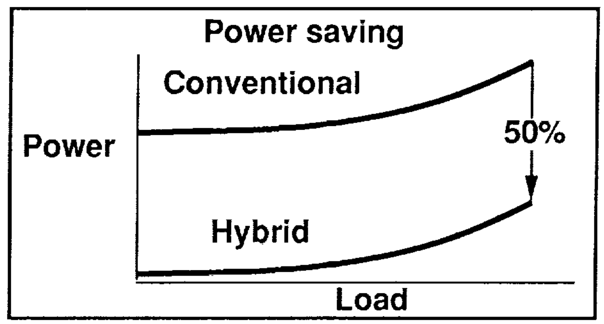
Hybrid Magnetic Bearing for Cryogenic To 400 °F Applications

Magnetic bearing with permanent magnet (PM) bias



Magnetic bearing components





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The second class of active vibration control techniques under development at Lewis is the magnetic bearing. Previous impediments in applying magnetic bearings to aerospace applications were the size, complexity, and weight of their control and power systems and the physical size of the magnetic bearing. Developments in control and power electronics have removed these barriers.

Magnetic bearings in turbomachines offer wear elimination, performance improvements, and potential weight savings. These advantages are achieved since there is no contact between the rotor and the bearing and since no lube system is required. Also, the stiffness and damping of the bearing can be varied, and the limits on shaft speeds and diameter can be substantially extended. Shaft vibrations can be minimized by properly modulating the electromagnetic forces applied to shaft through advanced digital controls, also under development.

Current research underway at Lewis is aimed at improving bearing load capacity and reducing bearing power consumption through implementation of hybrid bearing concepts such as the permanent-magnet-biased, magnetic bearing shown in the figure. In this concept the permanent magnets work in conjunction with the electromagnets to suspend the shaft. Relative to the conventional magnetic bearing (e.g., without the permanent magnet bias) the hybrid bearing reduces by 50 percent the power required to suspend and control the shaft under load. This concept produces less rotor heating which is important for very high-speed shafts. The other key advantage of this hybrid bearing design is the high radial load capacity. The design radial load capacity of the bearing shown is 500 lb for a 1-in.-diameter shaft. Depending on the final application, the magnetic bearing shown can operate over a broad temperature range of cryogenic to 400 °F.

National Aerospace Plane Engine Seals

Single stage-to-orbit
Mach 25 vehicle

High temperature
dynamic engine seals

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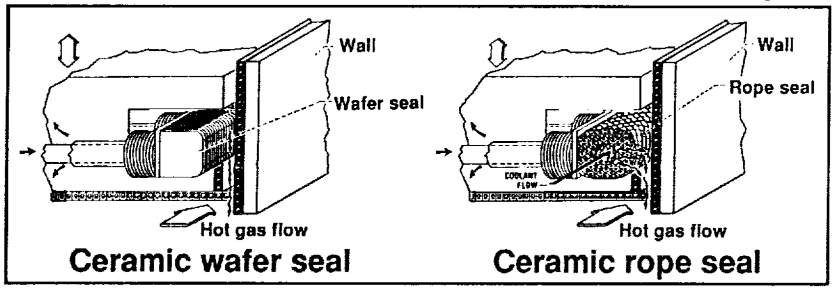
Key to the successful development of the single-stage-to-orbit National Aerospace Plane (NASP) is the successful development of combined cycle ramjet/scramjet engines that can propel the vehicle to 17 000 mph to reach low Earth orbit. To achieve engine performance over this speed range, movable engine panels similar to those used in advanced fighter jet two-dimensional exhaust nozzles are used to tailor engine flow. NASA Lewis is developing a family of new high-temperature seals to form effective barriers against leakage of extremely hot (>2500 °F), high pressure (up to 100 psi) flow path gases containing hydrogen and oxygen. Preventing backside leakage of these explosive gas mixtures is paramount in preventing the potential loss of the engines or the entire vehicle.

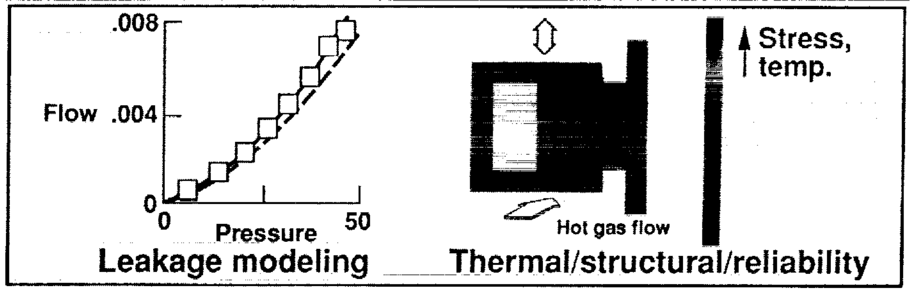
As shown in the engine isometric, the primary function of this sliding seal is to seal the many feet of linear gaps between the articulating horizontal engine panels and the adjacent vertical engine walls. Complicating the seal's mission is the need to accommodate and seal significant adjacent wall distortions (up to 3/16 in. in only 18 in. of seal length) caused by pressure and thermal loads on these weight minimized panels.

NASP Engine Seal Development

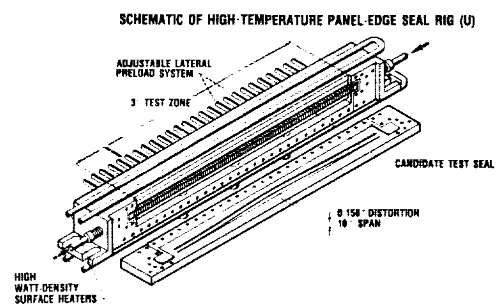


Concepts

Analysis



Performance tests



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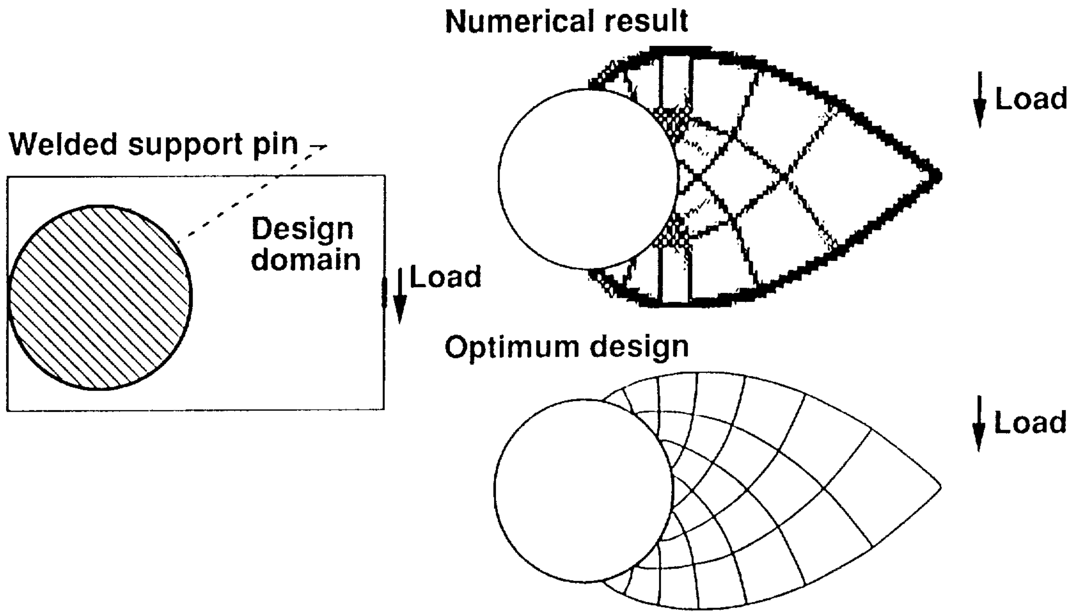
Advancements in state-of-the-art high temperature engine seals are being made by (1) developing advanced seal concepts fabricated from engineered ceramic materials, (2) developing and applying advanced analytical techniques to assess seal performance over the broad spectrum of engine operating conditions, and (3) finally demonstrating seal performance using specially designed high temperature test fixtures.

Two leading NASP engine seal candidates are the ceramic wafer seal and the braided ceramic rope seal shown. Both seals can operate hot to temperatures up to 2000 °F without coolant. The ceramic wafer seal derives its flexibility through relative sliding of the adjacent seal wafers. Low leakage, braided ceramic rope seals are made using advanced braiding techniques, under development, that take advantage of the high temperature flexibility of Nextel ceramic fibers. Analytical techniques recently developed under this program show promise in allowing seal designers to predict leakage flow through these braided preform seals as a function of engine operating conditions . Also, Lewis has developed and applied advanced iterative finite element techniques to assess wafer-seal thermal/structural and reliability performance under the extreme heating rates (up to 1160 Btu/ft^2-sec) expected during hypersonic flight.

Performance tests conducted at NASA Lewis have successfully demonstrated seal operation at engine simulated temperatures (up to 1350 °F), and pressures (up to 100 psi) sealing both flat and expected wavy wall conditions

Structural Shape Optimization

PROBLEM: Find minimum weight structure.
TEST CASE: Classic cantilever beam with overhung load.



CONSTRAINTS: Material strength, component weight, boundary conditions.

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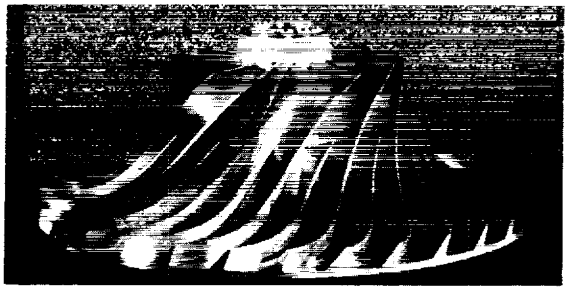
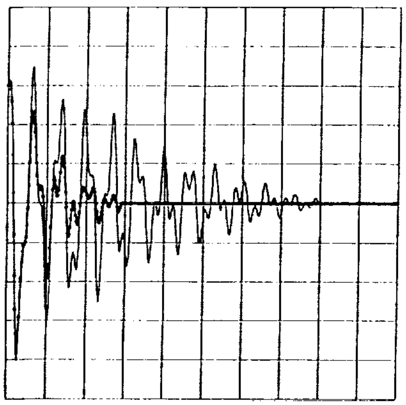
As part of the computational methods effort within the branch, automated techniques to perform structural optimization are under investigation in conjunction with the University of Michigan. A major difficulty of shape optimization of structures is caused by large domain changes during the optimization process that requires the rediscretization of the domain to conduct the finite element stress analysis. Furthermore, changes of topology, such as introduction of weight-saving holes in the structure, are virtually impossible with existing optimization approaches, unless done manually. To resolve these difficulties and limitations of traditional shape optimization, a new method has been developed. Optimization and discretization are performed in a fixed domain using a unit-cell approach to automatically generate the optimal shape and topology from a fixed domain, subject to given load and support conditions. The design domain is discretized into a grid-work pattern of unit-cells whose areas are modified sequentially until the compliance of the structure is minimized subject to a user-defined weight and material strength constraints. The unit-cell areas are tailored during the optimization using a percent-void parameter that varies between 0.0 for a heavily loaded (e.g., full) unit-cell and 1.0 for a lightly loaded (e.g., empty) cell.

The method was successfully demonstrated using the classical test case of a cantilever beam with an overhung load. The Michell truss shown in the lower right corner of the figure is the optimal (e.g., minimum weight) truss structure for carrying bending loads to a circular attachment pin. The structural shape predicted by the unit-cell shape optimization technique is shown in the upper right corner of the figure and bears a remarkable resemblance to the optimum. Structural designers using optimal shapes predicted from this method can easily mentally smooth the slightly irregular pattern and quickly complete the component's final design.

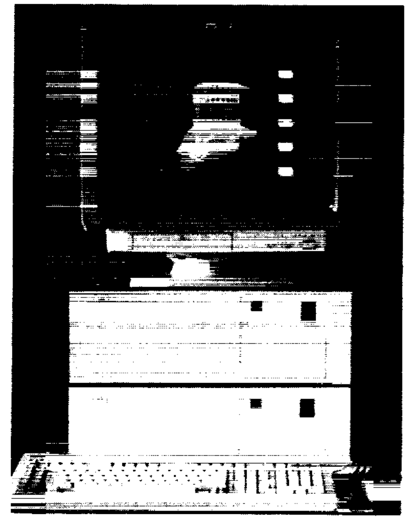
Dynamic Systems Analysis



Structural substructuring



Parameter identification



Hardware advancements
(e.g., transputer)

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To improve the speed and performance of structural dynamic computations, the researchers in the dynamic systems group are making advancements in the areas of (1) structural-dynamic substructuring methods, (2) parameter identification methods, and (3) computational methods. In the area of substructuring, specially developed boundary flexibility methods of component mode synthesis permit accurate dynamic calculations with significant reductions in computational time. Using parameter identification techniques which allow experimentally determined properties (e.g., stiffness and damping) to be entered into the numerical model allows much more accurate dynamic system performance calculations.

In the area of computational methods, advanced hardware architectures (such as parallel processors, neural networks, and transputers) along with computational strategies are being used to greatly improve solution efficiency of structural dynamic analysis problems.

For instance, Branch researchers using a specially developed 32-processor transputer demonstrated analysis times one-third that of a Cray X-MP24 in performing a finite element analysis of an SSME turbine blade. This speedup, combined with the relatively low-cost of the transputer system, gives this table-top workstation a performance-cost ratio of about 60 times better than the Cray X-MP24 system.

SUMMARY

Accomplishments and research-in-progress in the area of aeropropulsion have been reviewed for the Structural Dynamics Branch. Researchers in the areas of aeroelasiticty, vibrations control and dynamic systems are conceiving and implementing innovative structural concepts to enhance performance of advanced aeropropulsion systems and are developing and validating analytical techniques to define the limits of dynamic performance of advanced aero-engines, prior to costly full-scale testing.

Sophisticated aeroelastic methods under development are used to perform interactive fluid and structural analyses to define the performance limits (e.g., such as onset of blade flutter) of advanced turbine engines under both steady and unsteady conditions. Newly developed blade-forced response analyses go beyond defining performance limits and are being applied to predict blade dynamic displacements and blade cyclic stresses, allowing prediction of blade fatigue life.

To control unwanted shaft vibrations of advanced turbine engines vibration control researchers are developing two active-control techniques: piezoelectric actuators and magnetic bearing actuators. Combining high speed digital controls and advanced vibration sensing techniques with either of these active-control devices enables extension of engine performance limits and offers the new capability to squelch shaft vibrations caused by otherwise damage-producing transient conditions (e.g. hard landings or blade loss).

Researchers in the dynamic systems group are developing a new class of high temperature seals that show promise of meeting the demands of advanced hypersonic engines (e.g., NASP). Researchers are also developing and implementing advanced algorithms and computing hardware to improve solution speed, accuracy, and costs of large structural dynamics problems.